THE IMPORTANCE OF NONLINEAR MIXTURE MODELING FOR ANALYSIS OF LUNAR MULTISPECTRAL DATA. John F. Mustard, Lin Li, and Guoqi He, Department of Geological Science, Box 1846, Brown University, Providence RI, 02912. (John_Mustard@brown.edu)

Spectral mixture analysis (SMA) of lunar spectroscopic and multispectral data has been used with great success in a wide variety of applications on the Moon [1,2,3,4,5,6,7,8]. All published applications of SMA to lunar multispectral imaging data, without exception, use linear mixture modeling. For linear mixture modeling to be strictly valid, the endmember materials that are mixed must be arranged in physically discrete patches, as in a checkerboard. This assumption is probably not valid for typical endmember materials on the surface of the Moon. As has been demonstrated through numerous analysis of soils and cores from the Apollo landing sites (e.g. 9), the lunar surface is an intimate mixture of several lithologies, some of which have been transported from large distances. The pro-cess responsible for this mixing is meteorite bombard-ment of the surface which, through the impact process, causes lunar materials to be disaggregated and redistrib-uted on the surface. The spectral mixture systematics within an intimate mixture of endmember materials is well known to be a nonlinear problem [10-14].

If the objectives of an analysis of lunar spectral data are primarily to identify the spatial distributions of components and some general understanding of the physical abundance, then the linear mixture model approach is adequate. If, however, the objectives are to quantitatively determine the spatial relationships and physical abundances of components, and to understand and model processes responsible for the observations, then it is important to critically assess the linear assumption and employ a nonlinear mixture model if warranted. The difference in abundances between a lin-ear and nonlinear solution can be significant, and may change the interpretation of the processes at work. In this analysis, linear and nonlinear mixture models are applied to Clementine UV-VIS multispectral data of mare-highland boundaries. We are studying the magni-tude of material transport across these boundaries. The results are compared, and show that the inter-pretation of mixing processes are fundamentally different bet-ween the linear and nonlinear solutions.

Calibration of Clementine Data: The Clementine data for the 5 UV-VIS filters were calibrated using the standard methods developed the Clementine team [15,16]. Briefly, this involves corrections for gain and offset, dark current, frame transfer, flat field, photo-metric correction, and spectral calibration. Following this calibration, the data are within 5% of absolute, and have been normalized to an i=30° and e=0° observation geometry. This photometric normalization is based on a highly generalized model for the photometric behavior of the lunar surface, and is the most valid for original observations with 20°< i < 40°.

Mixture Modeling: The basic approach of mixture modeling is to fit, using the technique of least squares, a suite of spectral endmembers to an observed spec-trum, subject to the constraint the sum of the fractions is equal to 1.0 [17] As long as the number of end-members does not exceed the number of spectral chan-nels, a solution exists, though for the lunar surface the number of endmembers is generally less than the five UV-VIS channels. In typical applications three end-members are resolved: one each for mare, highland, and fresh crater materials. In complex or spectrally diverse areas, an additional mare, highland, or fresh crater endmember may be resolved, but not all three.

Although the reflectances of intimate mixtures are a nonlinear combination of the reflectances of the endmembers, the mixing systematics are predicted to be linear if the reflectances are converted to single-scattering albedo [10, 18]. Thus the same general approach is employed in nonlinear spectral mixture modeling, except the calibrated reflectance data are converted to single-scattering albedo before selecting endmembers and computing fractions. To convert to SSA, we employ the equations of [10] for radiance coefficient, subject to the following assumptions: the opposition surge is negligible at the i=30° and e=0° geometry, and the lunar surface scatters light isotropically. The second assumption is justified on the basis that many surfaces approximate lambertian behavior at i=30° and e=0° [13].

Results for Mare-Highland Boundaries: Both the linear and nonlinear approaches have been applied to mare-highland boundaries in Grimaldi and Tsiolkovskiy. The details of these analyses and the implications for lateral and vertical transport of material on the moon are reported elsewhere [7, 19]. In general, the average RMS error of the solutions is lower for the nonlinear than the linear approaches (≈1% for linear, ≈0.2% for nonlinear), but the spatial information in the RMS error images is unchanged. In this analysis, we are concerned with the differences between results for linear and nonlinear approaches. Shown in Figure 1 are profiles of mare abundance across the southern mare-highland boundaries in Grimaldi, and in Figure 2 are shown the differences between linear and nonlinear mare abundances for the same profiles. The difference between linear and nonlinear abundances plotted as a function of %mare from the nonlinear solution is shown in Figure 3.

Although the linear and nonlinear abundance profiles may not appear significantly different, in detail the differences are very significant. The maximum difference between the linear and nonlinear solutions is where the mare abundance is ≈50%, as expected from theoretical considerations, and is on the order of 10-15% (Fig. 2, 3). We have identified the location of the geologic contact (determined on the basis of morph-ology) in each of these profiles. For the linear solu-tions, the contact typically occurs at a mare abundance of 60%, while for the nonlinear solutions, the mare contact typically occurs at a mare abundance of 50%. The linear solutions predict much greater amounts of mare on the highland side of the contact than the nonlinear solutions (Fig. 3). Finally, the mixing profiles are asymmetric with the linear solutions, but symmetric with the nonlinear solutions (Fig. 1).

Conclusions: Clearly, the interpretation of the physical processes causing mixing across mare-highland boundaries is strongly affected by the choice of a linear Vs a nonlinear mixture analysis. For the linear solutions, the mixing systematics are asymmetric, with much more mare apparently transported to the highlands, and the mare abundance at the geologic contact is 60%. This result is somewhat puzzling, as most models for lateral transport would predict the opposite. For the nonlinear solutions, however, the mixing process is apparently very symmetric. The geologic contact occurs where the mare abundance is 50%, and equal amounts of mare are transported to the highlands as are highlands to the mare. This implies that vertical mixing is unimportant for this boundary.

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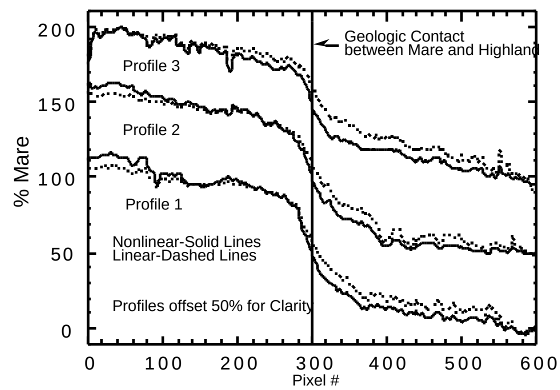

Figure 1. Profiles of mare abundance across the Grimaldi mare-highland geologic contact.

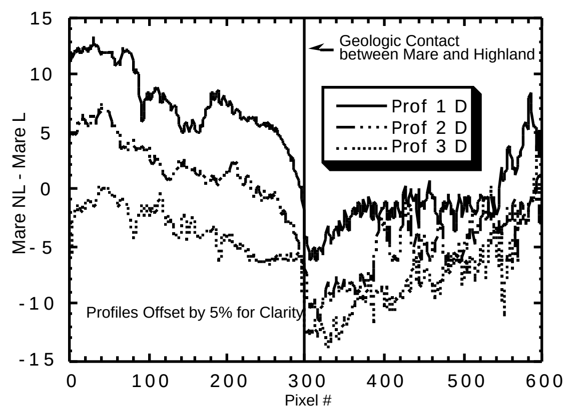

Figure 2. Profiles of the difference of linear mare abundance from nonlinear mare abundance across the Grimaldi mare-highland geologic contact.

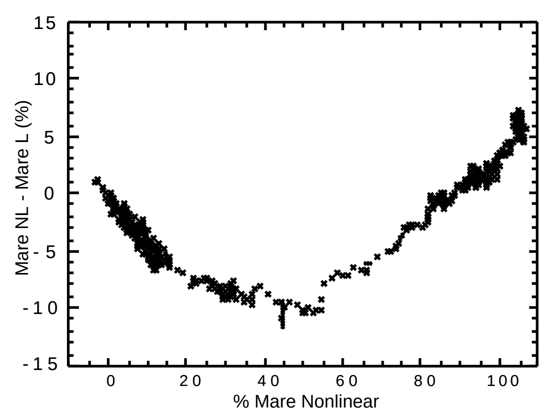

Figure 3. Difference of linear from nonlinear mare abundance plotted as a function of %mare determined with the nonlinear model.